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(54) MICROMACHINED X-RAY IMAGE CONTRAST GRIDS

(75) Inventors: **Jeffrey T. Rahn**, Mountain View; **Raj B. Apte**, Palo Alto, both of CA (US)

(73) Assignee: **Xerox Corporation**, Stamford, CT (US)

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(22) Filed: **Nov. 24, 1999**

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(52) **U.S. Cl.** **378/154**; 378/149
(58) **Field of Search** 250/508.1; 378/145, 378/147, 149, 154

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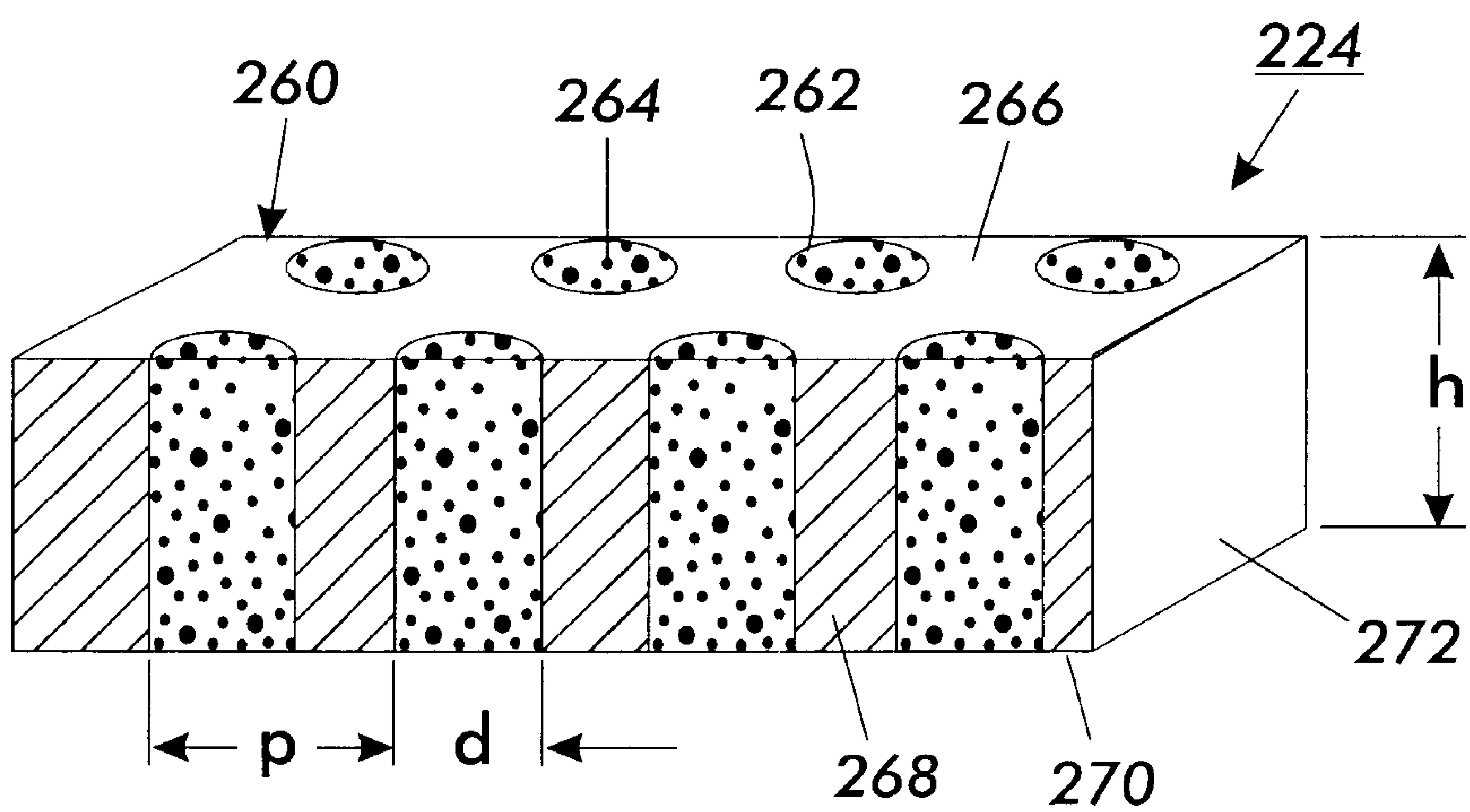
Primary Examiner—David P. Porta
(74) *Attorney, Agent, or Firm*—Oliff & Berridge, PLC

(57) **ABSTRACT**

Image contrast grids include a body having openings and an x-ray absorbing material in the openings. The openings can be formed by various micromachining techniques and the x-ray absorbing material can be formed in the openings by various coating and deposition techniques. The image contrast grids can have contoured surfaces for improved focusing capabilities. The image contrast grids can remove Compton scattered x-rays in two, non-normal dimensions. The openings can be formed with fine structures that are not visible in most imaging modes.

37 Claims, 8 Drawing Sheets



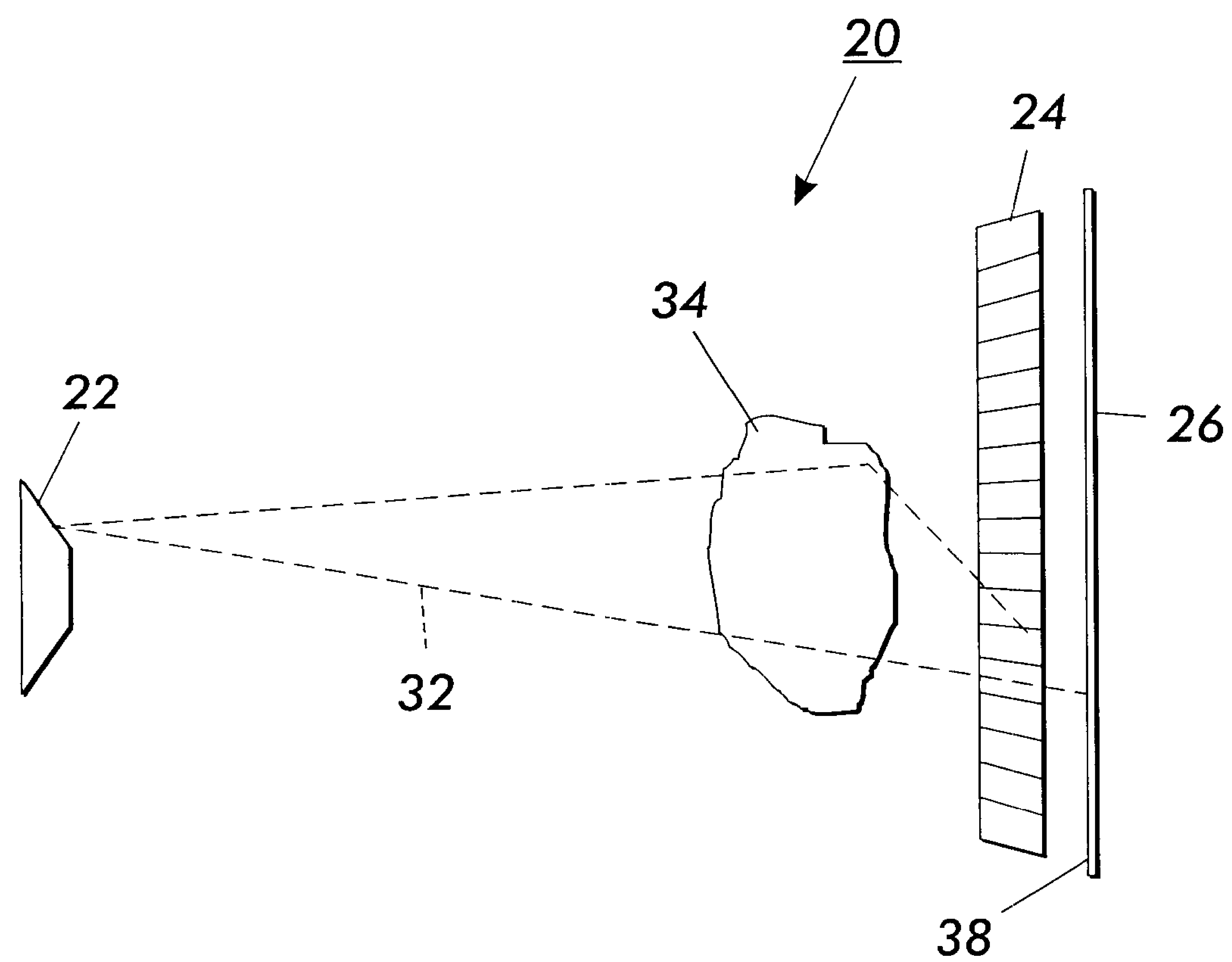


FIG. 1

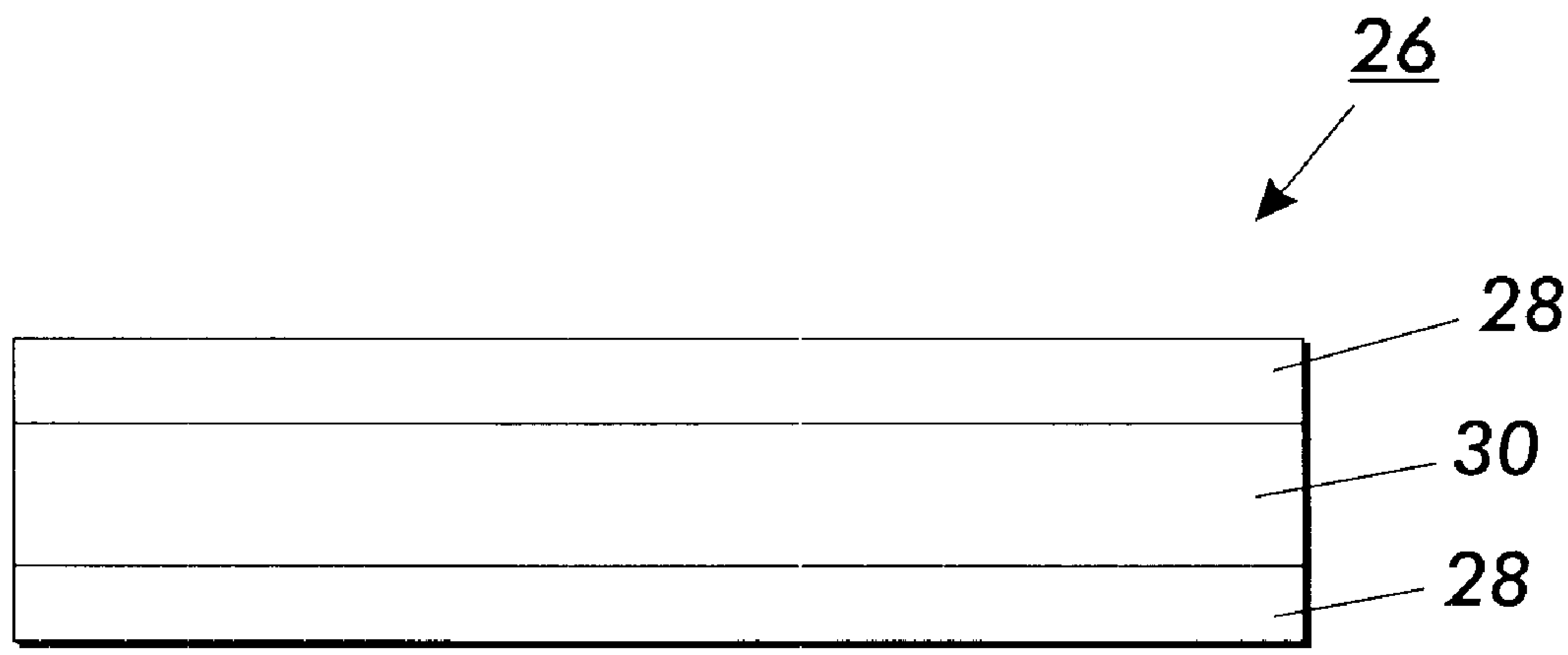


FIG. 2

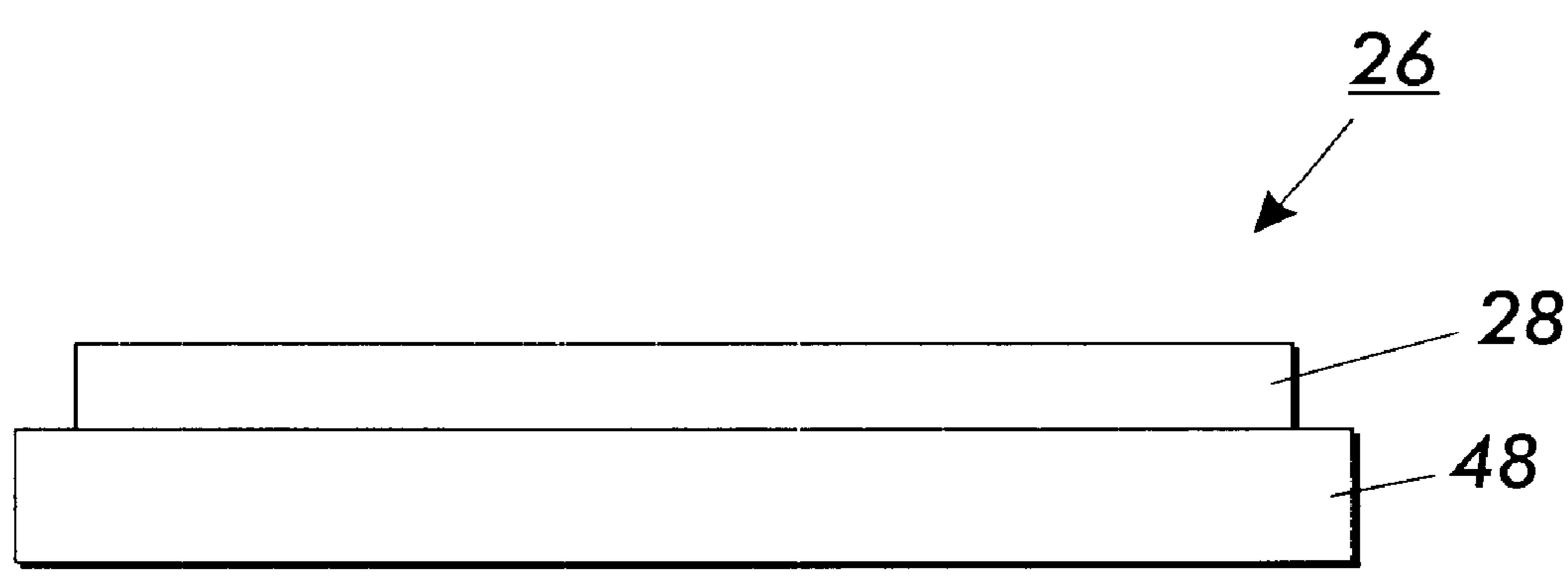


FIG. 3

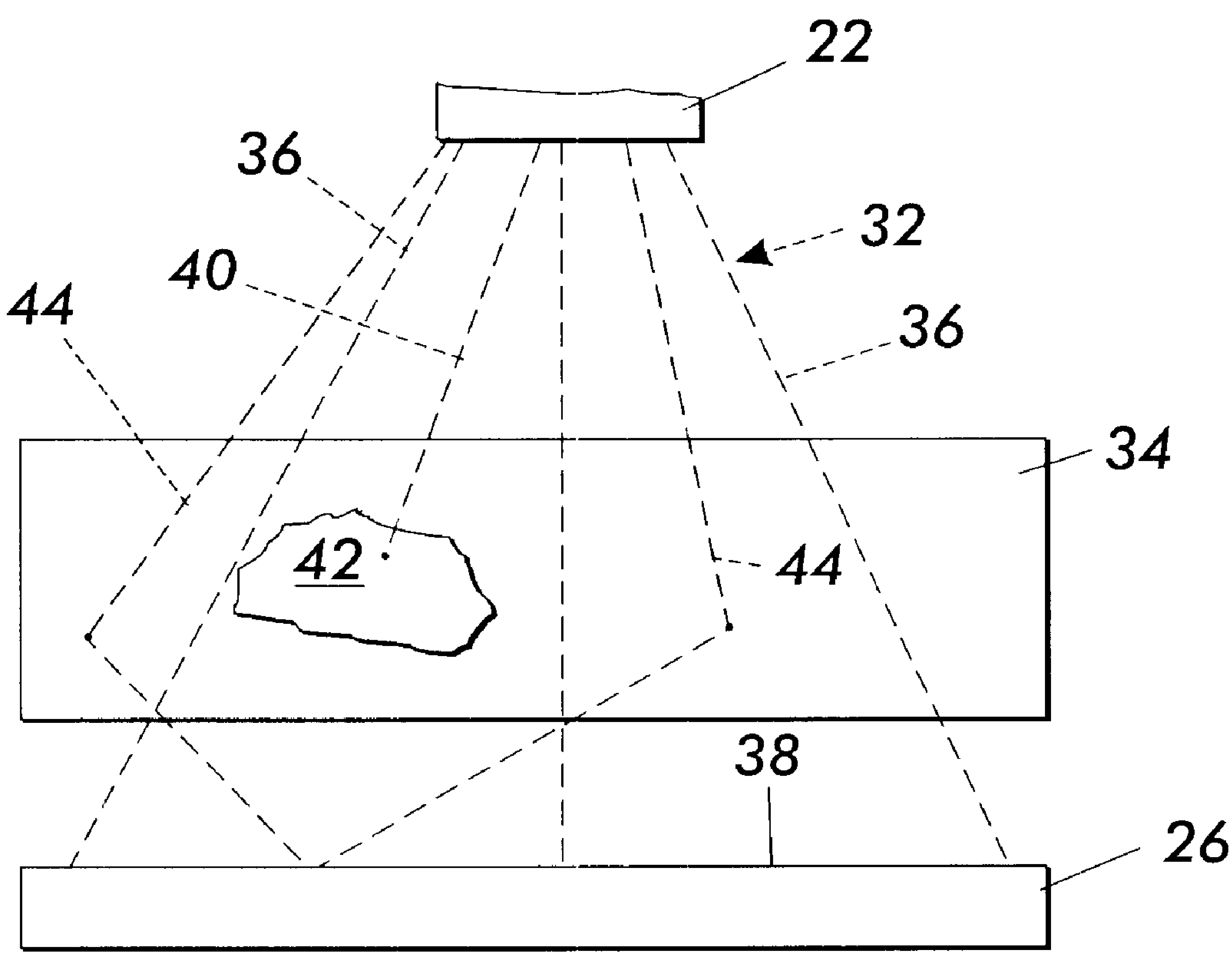


FIG. 4

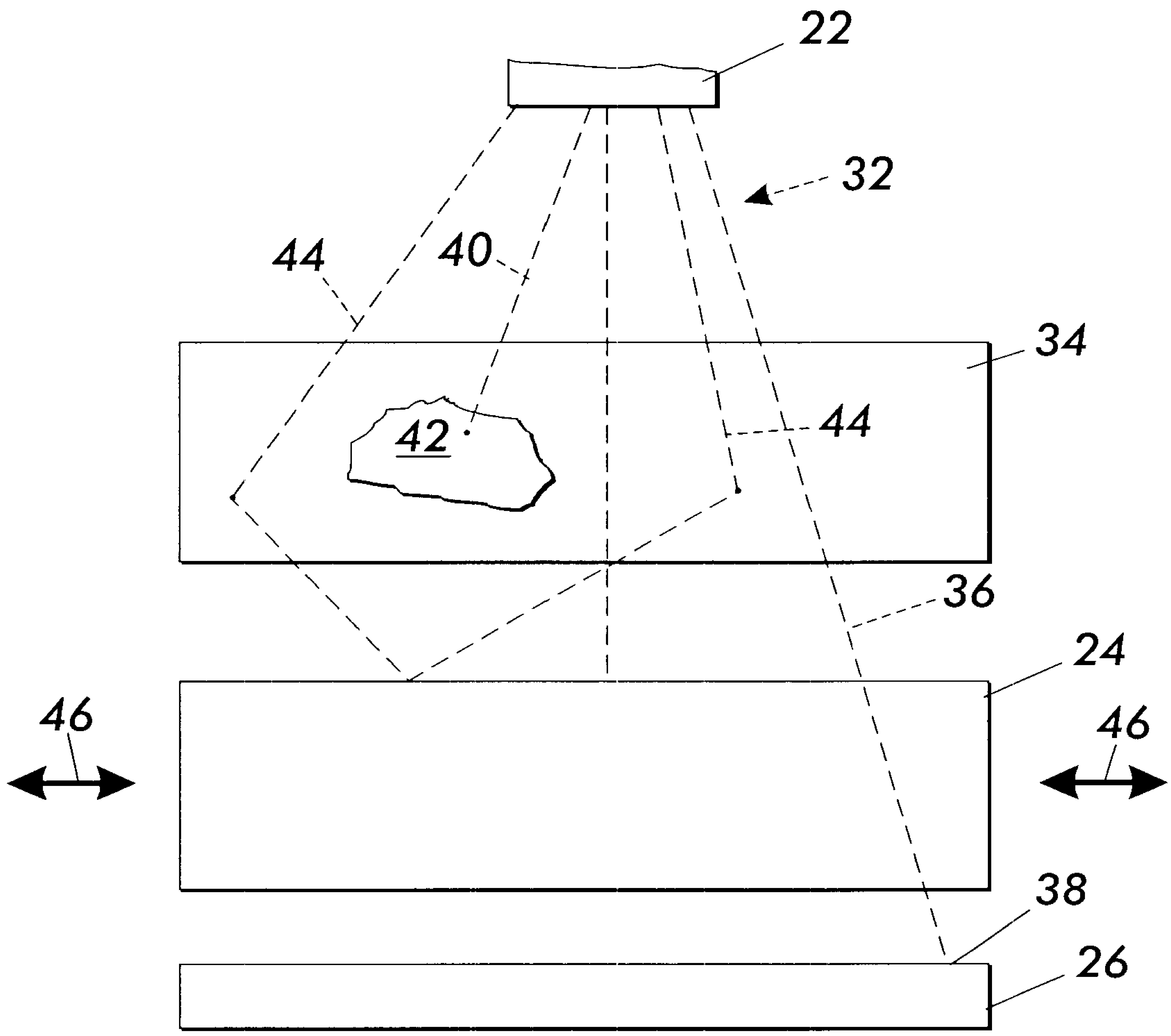


FIG. 5

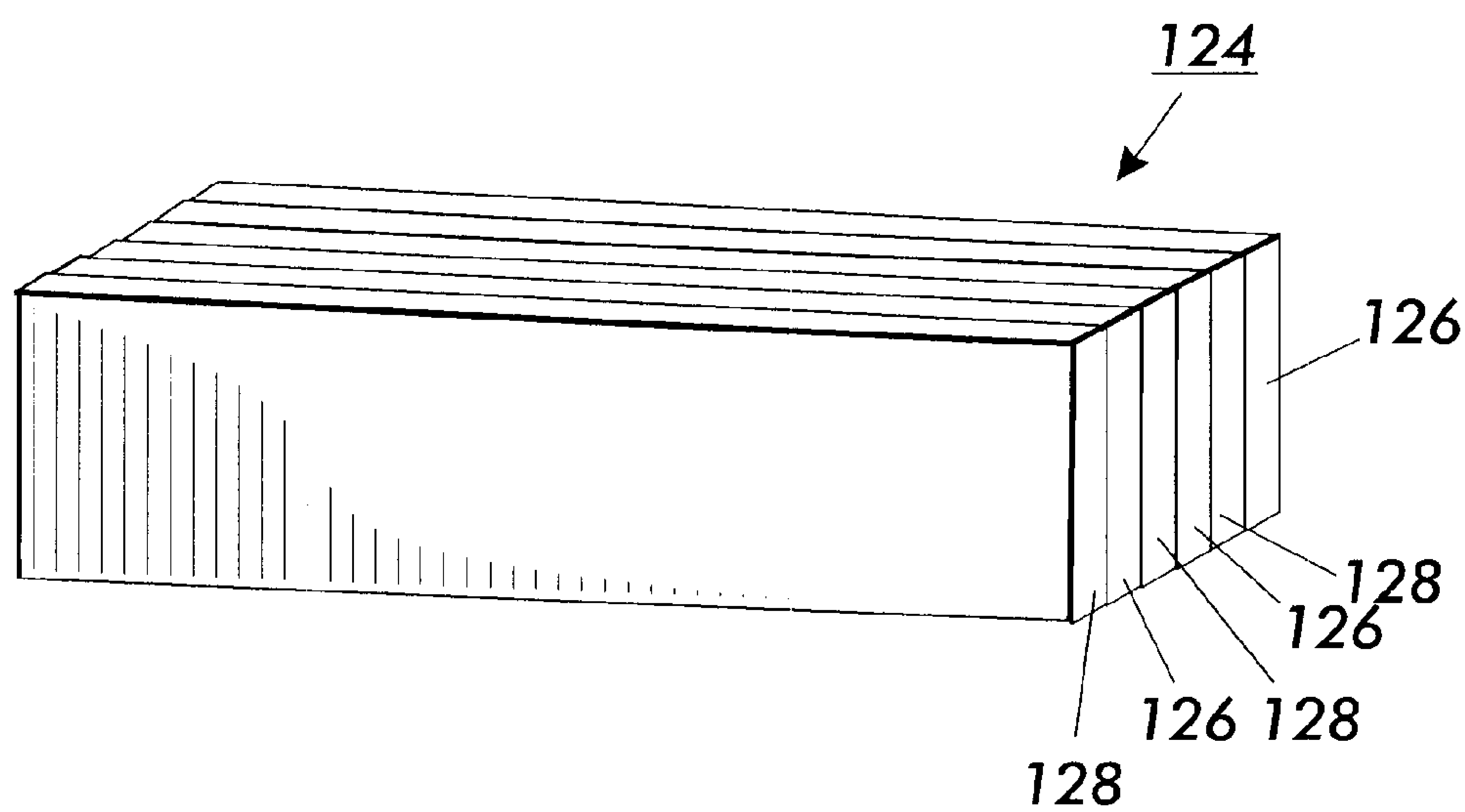


FIG. 6

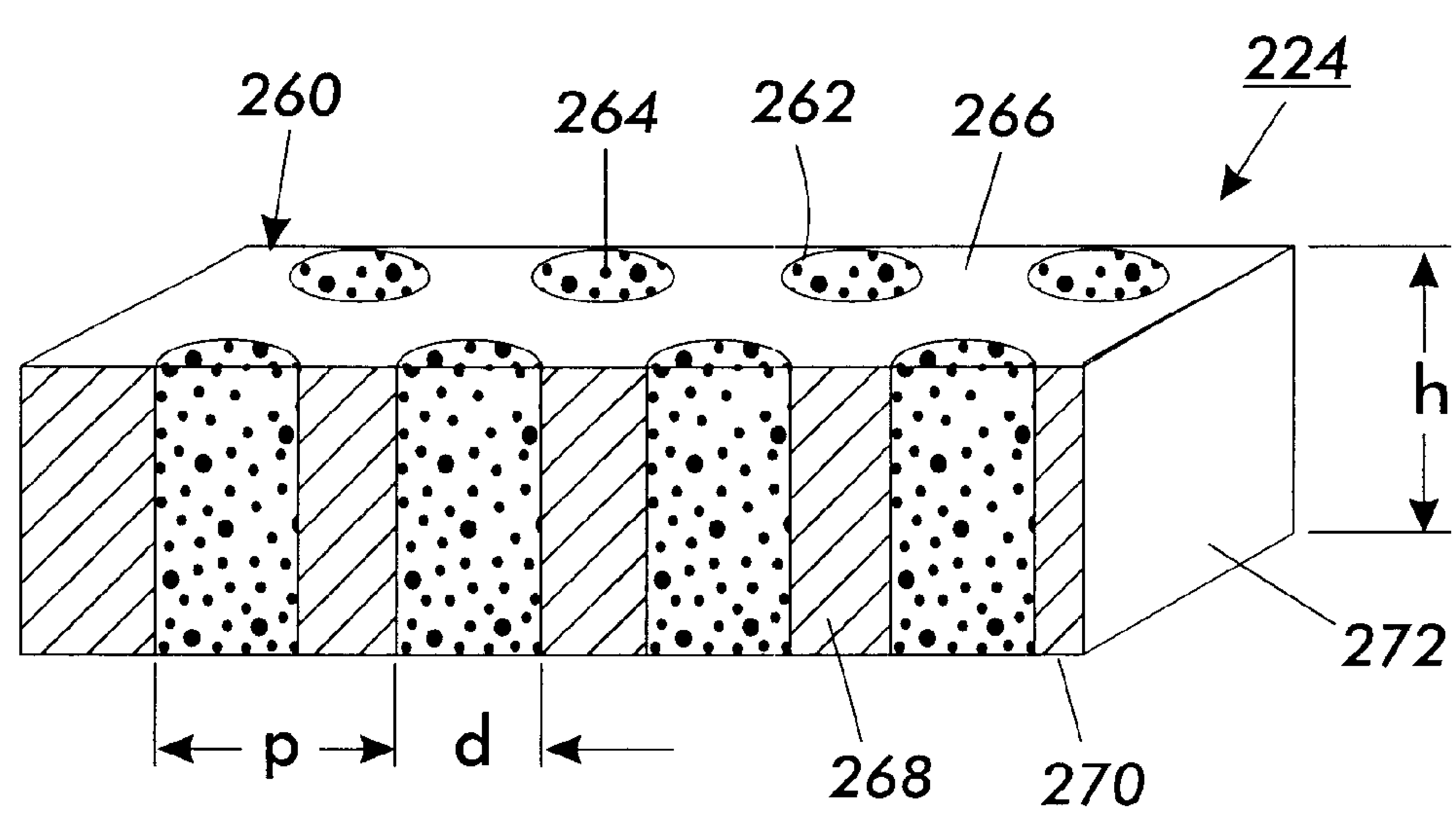


FIG. 7

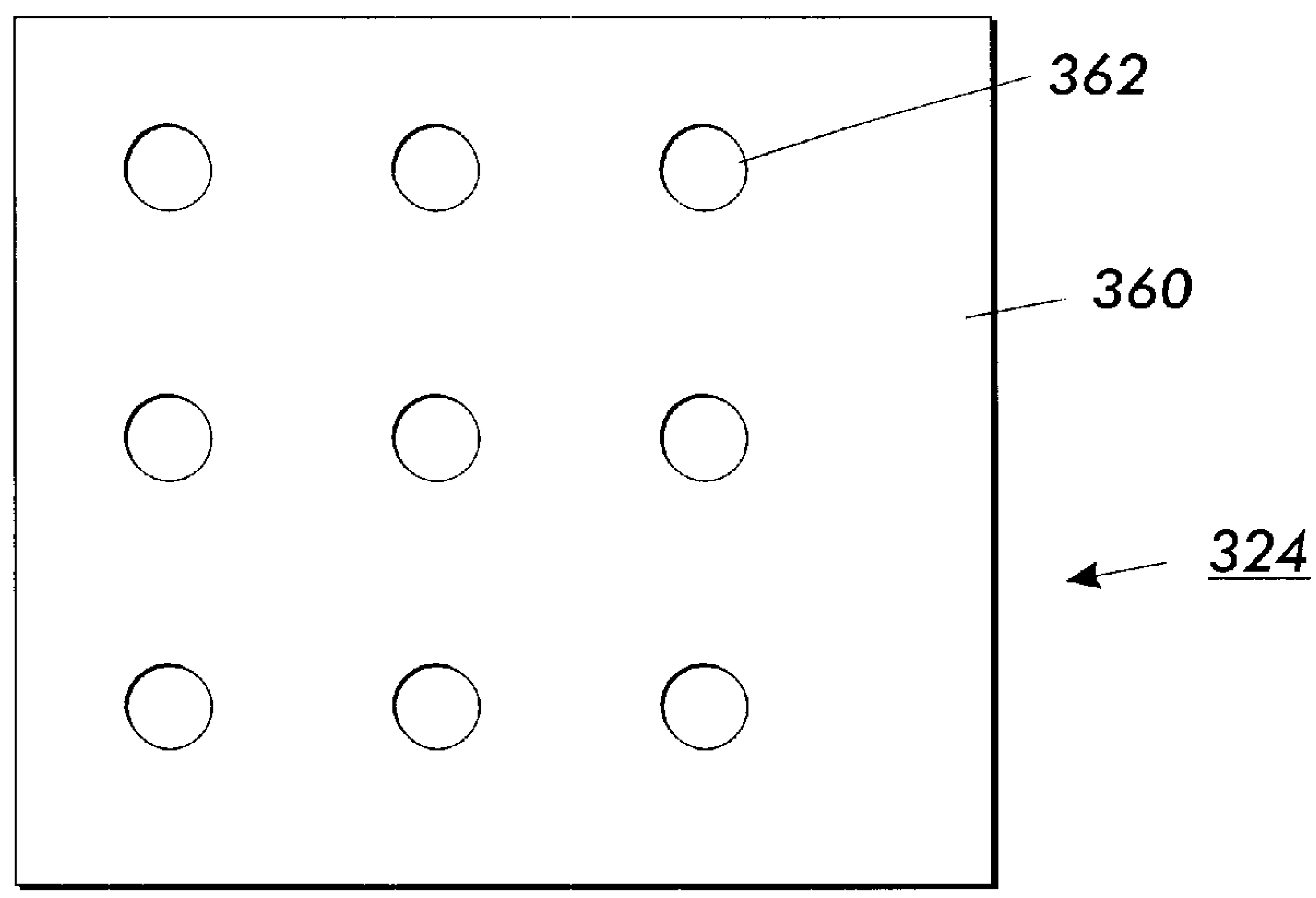


FIG. 8

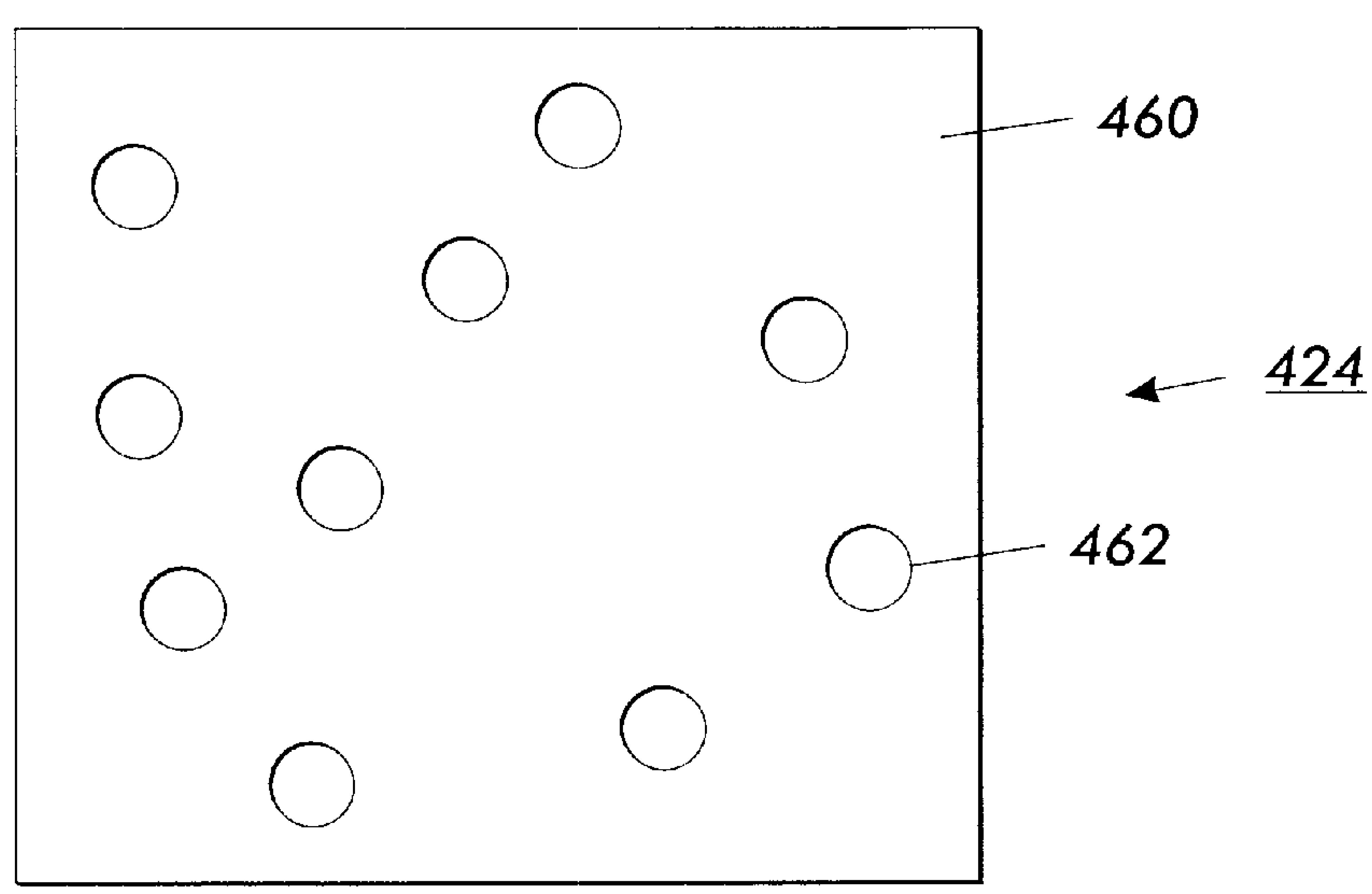


FIG. 9

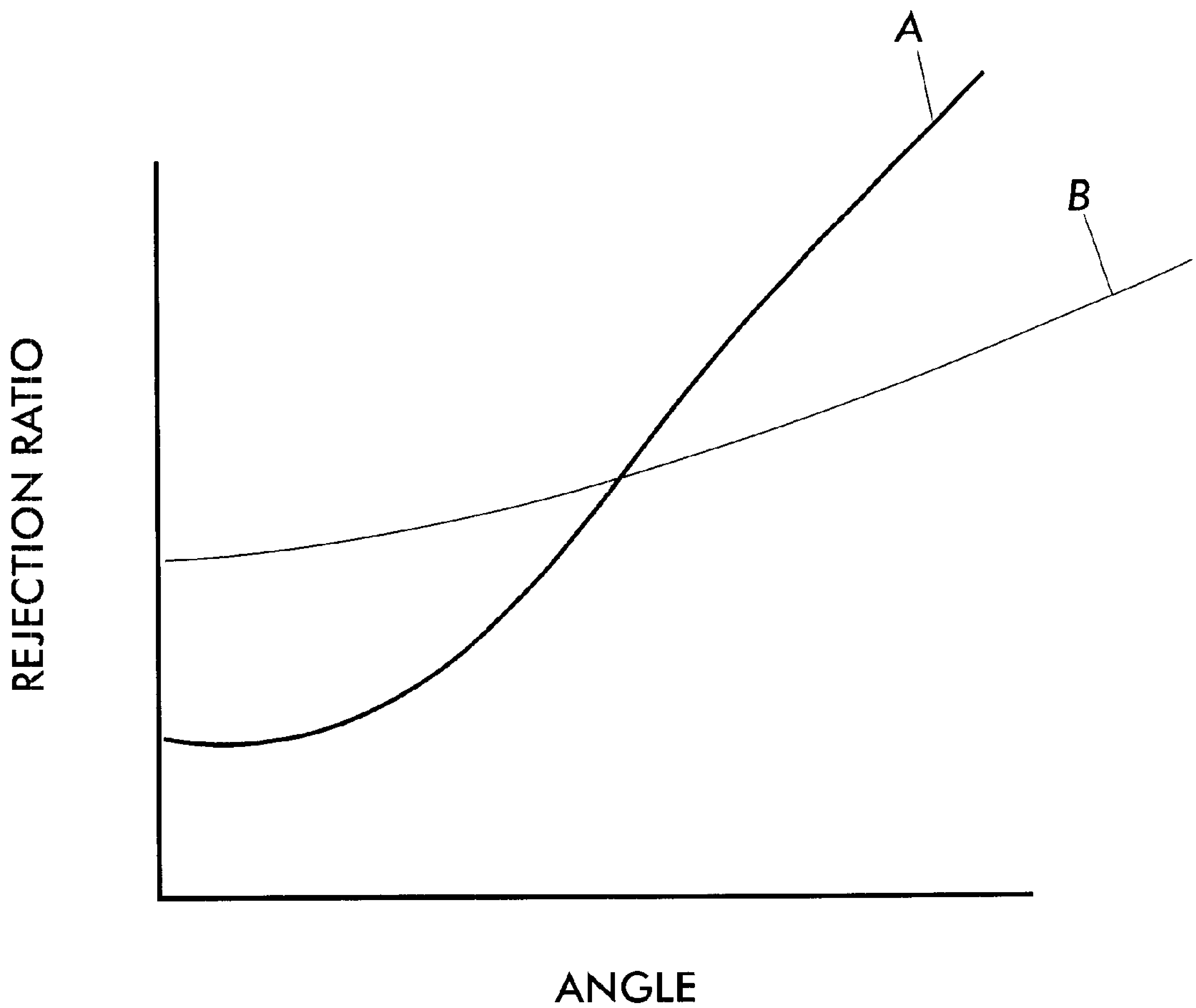


FIG. 10

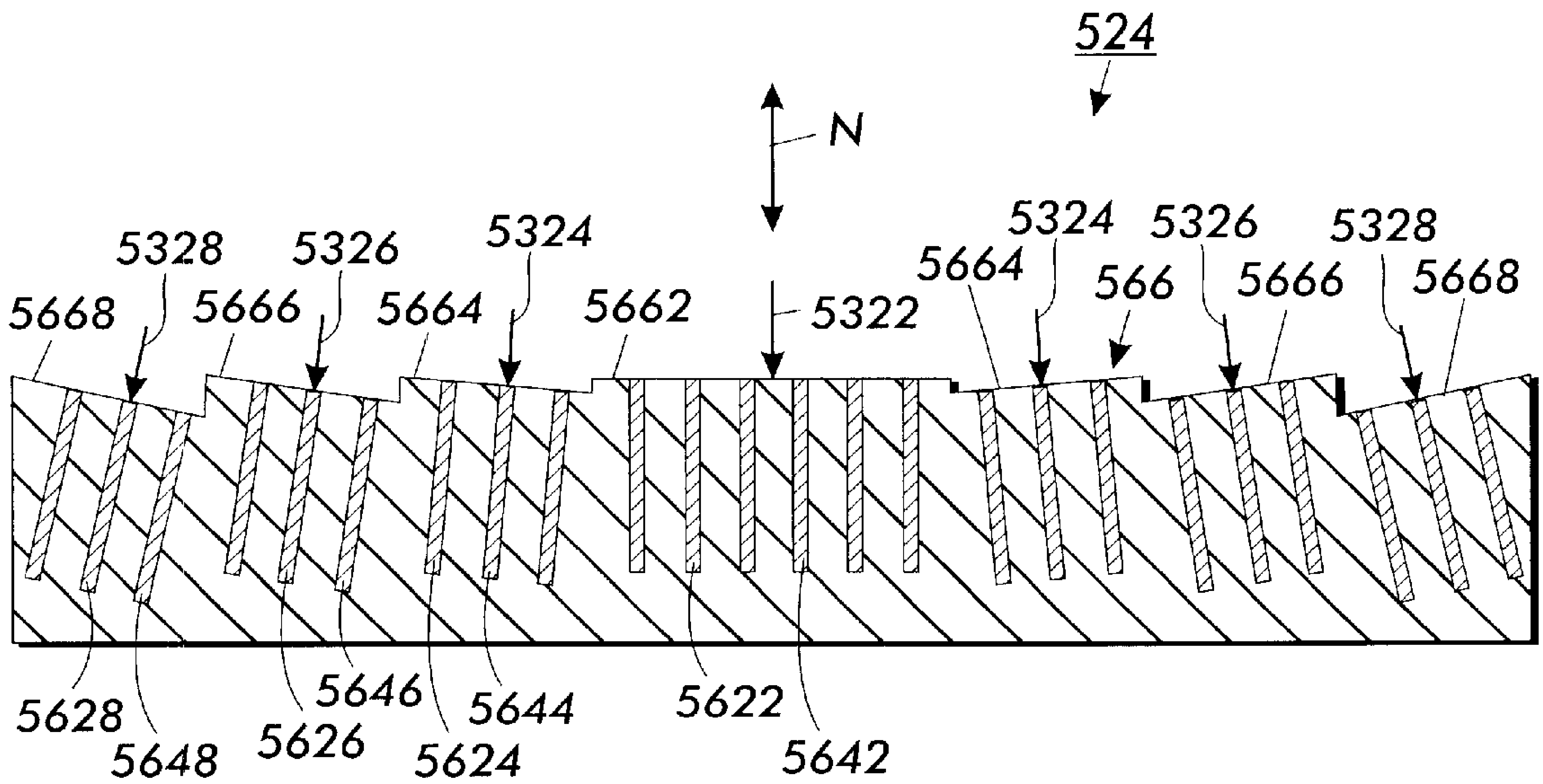

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FIG. 11

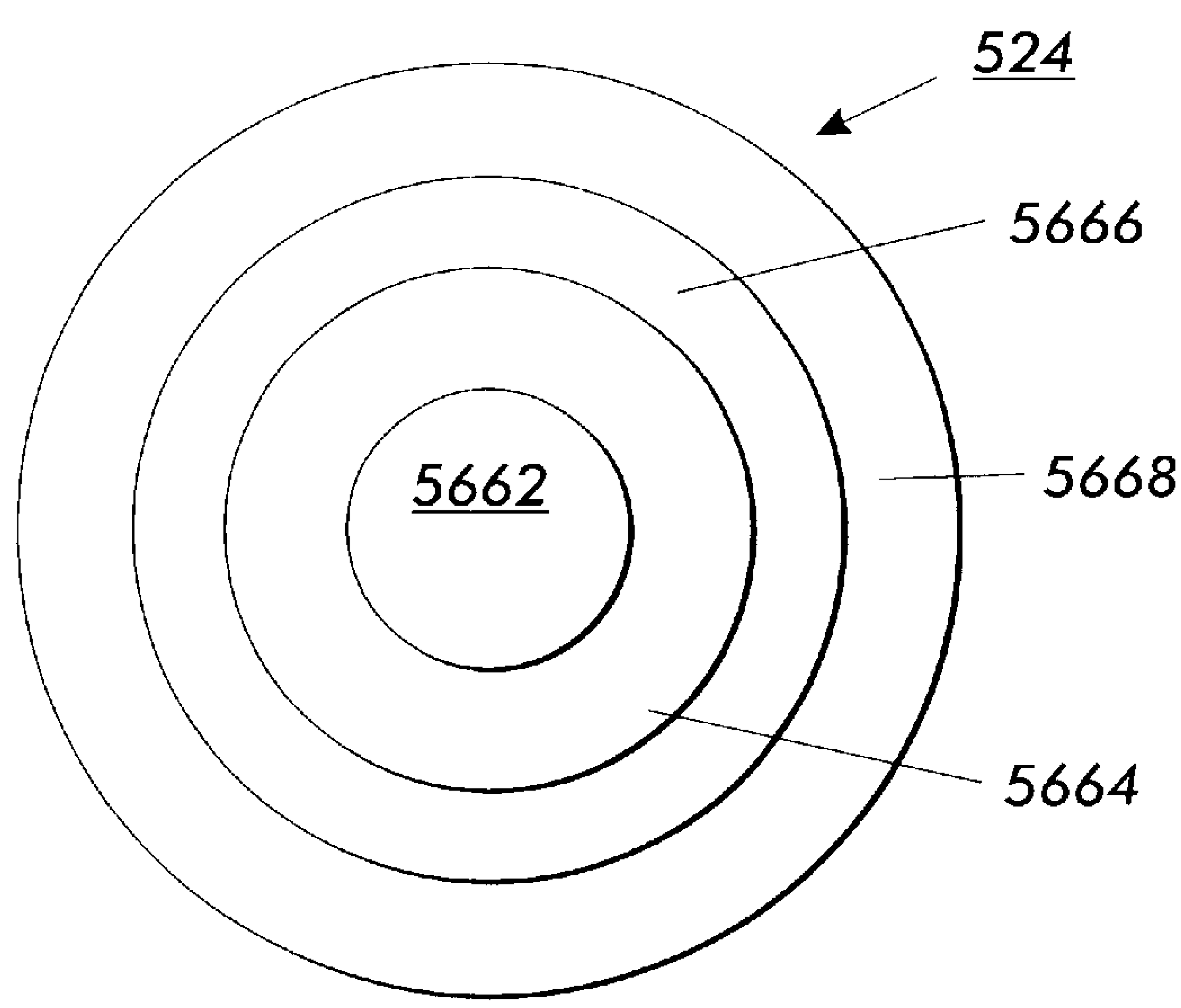
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FIG. 12

MICROMACHINED X-RAY IMAGE CONTRAST GRIDS

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention relates to the field of x-ray imaging.

2. Description of Related Art

X-ray radiation is widely used for medical x-ray imaging and non-destructive evaluation. X-ray radiation easily penetrates many materials and allows images to be taken based on the shadows of dense materials that absorb x-rays. X-ray imaging is used for both thick and thin tissue procedures in medical imaging radiology and fluoroscopy. Exemplary applications of x-ray imaging in non-destructive evaluation include the testing of buildings, structural members, pressure vessels, welds and airplane fuselage constructions, and the like for the presence of defects and structural integrity.

SUMMARY OF THE INVENTION

The application of x-ray imaging presents difficult technical problems. One particular problem is that the absorption of x-rays by materials at higher energies (greater than 100 keV) competes with the Compton scattering process. Compton scattering deflects x-rays through a small angle from their original trajectories. For imaging dense and/or thick materials, Compton-scattered x-rays can obscure the image formed by the absorption of direct unscattered x-rays.

FIG. **1** shows a conventional x-ray imaging system **20** configuration for imaging objects. The x-ray imaging system **20** comprises an x-ray source **22** and an image contrast grid (antiscatter grid) **24** placed between the x-ray source **22** and a detector **26**. The x-ray source **22** emits x-rays **32** that impinge on an object **34** to be imaged. For example, the object **34** can be a human body. The transmitted x-rays **36** strike the surface **38** of the detector **26**.

As shown in FIG. **2**, the detector **26** may include a film cassette with a film **30** sandwiched between phosphors **28**. As shown in FIG. **3**, the detector **26** may alternatively include an electronic detector such as an a-Si detector **48** combined with a phosphor or photoconductor **28** as described in J. Rahn et al., "High Resolution, High Fill Factor a-Si:H Sensor Arrays for Optical Imaging," *Materials Research Society Proc*. 557, April 1999, San Francisco, Calif.; and R.A. Street, "X-ray Imaging Using Lead Iodide as a Semiconductor Detector,"*Proc. SPIE 3659, Physics of Medical Imaging*, Feb. 1999, San Diego, Calif., each incorporated herein by reference in its entirety.

As shown in FIG. **4**, some of the non-normal x-rays **40** strike dense material **42** in the body, such as bone, and are absorbed by the dense material. However, other x-rays **44** are scattered and do not strike the dense material **42** and pass through the soft body tissue without being absorbed. These scattered x-rays are known as Compton-scattered x-rays.

The Compton-scattered x-rays **44** that do not strike dense material **42** in the object **34** adversely affect the formed image of the dense material. That is, the Compton-scattered x-rays **44** exit from the object **34** at positions that are laterally spaced from the positions at which they entered the object **34**. Based on their exit locations, the Compton-scattered x-rays **44** would appear to have passed through the region of the object **34** where the dense material **42** is located, but without having been absorbed by the dense material **42**.

As shown in FIG. **5**, the image contrast grid **24** is provided in the x-ray imaging system **20** to absorb the Compton-scattered x-rays **44** that are not absorbed by dense material **42** in the object **34**. The Compton-scattered x-rays **44** affect the darkness (contrast) of the image of the dense material **42** that is formed by the actual absorption of the x-rays **40** by the dense material **42**. The image contrast grid **24** reduces the effects of the Compton-scattered x-rays **44** on the image formed by the absorption of direct x-rays by eliminating the Compton-scattered x-rays **44** that travel in a direction through the object **34** that does not point to the x-ray source **22**. By eliminating the Compton-scattered x-rays **44**, the image contrast is enhanced.

In general, image contrast grids are required for all "thick" tissue medical imaging procedures; i.e., procedures in which the screen is not located close (within about the thickness of the screen) to body tissue during medical imaging procedures.

Image contrast grids have been formed by laminating together foils of x-ray transparent material, such as aluminum, and x-ray absorbing material, such as lead, to form an extended sandwich structure. FIG. **6** illustrates a known sandwich structure image contrast grid **124** including aluminum foils **126** and lead foils **128** forming an alternating, parallel arrangement.

Other methods of forming image contrast grids have been described, for example, in U.S. Pat. Nos. 5,581,592 and 5,557,650, incorporated herein by reference in their entirety.

However, known image contrast grids, such as the image contrast grid **124**, and the processes for forming the grids are unsatisfactory for at least several reasons. First, these processes are complicated and expensive to perform, leading to a high cost of the grids.

Second, known image contrast grids, such as the image contrast grid **124**, have a relatively coarse structure that produces grid lines in the formed images. For example, to reduce this problem, the grids can be moved slightly back and forth in a direction **46** approximately perpendicular to the normal (i.e., the direction of the x-rays **36**) to blur the image of the grid lines formed on the film. This movement of the grids is known as the "Bucky system." However, the Bucky system requires the imaging system to include additional components and, thus, increases the cost and complexity of the system.

Third, known image contrast grids, such as the image contrast grid **124**, only remove the Compton-scattered, non-normal (off-z-axis) photons in one dimension (i.e., along either the x-axis or the y-axis). In order to provide two-dimensional photon removal using these grids, two grids, such as two of the image contrast grids **124**, have been stacked with their respective foils oriented orthogonal with respect to those of the other grid. Although the combined use of two grids may improve Compton-scattered photon removal in a second direction, the cost of the imaging system is also significantly increased by the added cost of the second grid. Thus, the value of improving the performance of the imaging system by using two image contrast grids may not justify the associated added cost to achieve the improved performance.

This invention provides improved image contrast grids that can overcome the above-described problems of the known image contrast grids and the processes used to form the known image contrast grids.

This invention separately provides image contrast grids that have improved x-ray transmission efficiencies, i.e., rejection ratios, that thus reduce the required dosage of source radiation that is needed to obtain an image of an object.

This invention separately provides image contrast grids that have increased open aperture ratios.

This invention separately provides image contrast grids that can be used to form images with improved contrast.

This invention separately provides image contrast grids that have fine structures that reduce or eliminate the need to use a Bucky system during imaging.

This invention separately provides image contrast grids that remove Compton-scattered x-rays in two, co-planar dimensions, e.g., the x and y dimensions, and thus eliminate the need to use two image contrast grids simultaneously.

This invention separately provides methods of making the image contrast grids that are economical, controllable and reproducible.

This invention separately provides methods of using the image contrast grids in imaging systems for imaging objects.

Various exemplary embodiments of the image contrast grids according to this invention comprises a body forming a continuous matrix and openings. The body comprises one of a first material that is at least substantially transparent to x-rays and a second material in the openings that absorbs the x-rays without substantially scattering the x-rays. Another of the first material and the second material is disposed in the openings. The body includes a first surface where the x-rays enter the image contrast grid and a second surface opposite to the first surface where the x-rays exit the image contrast grid. The openings extend at least partially from the first surface to the second surface.

In some exemplary embodiments, the first surface of the body is machined to provide enhanced focus capabilities.

This invention also provides x-ray imaging systems to image objects that comprise an x-ray source that emits x-rays and an image contrast grid positioned such that x-rays emitted by the x-ray source pass through the object and impinge on the first surface of the image contrast grid. An image plane faces the second surface of the image contrast grid.

In various exemplary embodiments of the x-ray imaging systems according to this invention, the image contrast grid can be maintained stationary during imaging without forming grid lines on the formed image of the object. Thus, in various exemplary embodiments of the x-ray imaging system, it is not generally necessary to use a Bucky system during imaging. The image contrast grids according to this invention remove Compton scattered x-rays that pass through the object in two coplanar dimensions of the image contrast grid.

Exemplary embodiments of the methods of making image contrast grids comprise forming the body including the openings. The x-ray absorbing material can be formed in the openings or the x-ray absorbing material can be used to form the body. The openings and the x-ray absorbing material can be formed by various exemplary embodiments of the methods according this invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of this invention will be described in detail, with reference to the following figures, in which:

FIG. **1** illustrates an x-ray imaging system configuration;

FIG. **2** illustrates an exemplary detector;

FIG. **3** illustrates another exemplary detector;

FIG. **4** illustrates the Compton scattering of x-rays by an object in an x-ray imaging system without an image contrast grid;

FIG. **5** illustrates the Compton scattering of x-rays by an object in an x-ray imaging system including an image contrast grid between the object and the screen;

FIG. **6** illustrates a known image contrast grid structure;

FIG. **7** illustrates an exemplary embodiment of an image contrast grid according to this invention;

FIG. **8** illustrates an exemplary embodiment of an image contrast grid according to this invention having a regular pattern of openings;

FIG. **9** illustrates another exemplary embodiment of an image contrast grid according to this invention having a random pattern of openings;

FIG. **10** illustrates the relationship between the rejection ratio and the angle of incidence of the x-rays for a known image contrast grid structure and for an image contrast grid according to this invention;

FIG. **11** is a side view of a portion of another exemplary embodiment of an image contrast grid according to this invention having a contoured top surface; and

FIG. **12** is a top view of the image contrast grid of FIG. **11**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

This invention provides improved image contrast grids for use in x-ray imaging applications. As described in detail below, the image contrast grids have improved rejection ratios and also reduced fill factors, i.e., increased open aperture ratios. Accordingly, the grids can improve image quality. In addition, the grids can provide increased efficiency and thus reduce the required dosage of source radiation that is needed to obtain an image of an object. In addition, the grids can have fine structures that reduce or even eliminate the need for the use of a Bucky system during imaging.

This invention also provides methods of making the image contrast grids that are economical, controllable and reproducible. The methods can provide consistent grid structures in a cost-efficient manner.

This invention also provides methods of using the image contrast grids in imaging systems for imaging objects such as bodies.

FIG. **7** shows an exemplary embodiment of an image contrast, or antiscatter, grid **224** according to this invention. The image contrast grid **224** comprises a body **260** that includes a plurality of openings **262**. The body **260** forms a continuous matrix. In various exemplary embodiments, the openings **262** have an elongated, generally cylindrical configuration.

An x-ray absorbing material **264** is formed in the openings **262** in the body **260**. As shown, in some exemplary embodiments of the image contrast grids **224** according to this invention, the x-ray absorbing material **264** can be formed to substantially fill the openings **262**. In these exemplary embodiments, the x-ray absorbing material **264** can fill the openings along the entire length of the openings **262** as shown.

Alternatively, the x-ray absorbing material **264** can fill the openings **262** only along selected portions of their length. For example, the x-ray absorbing material **264** can be formed only near the top surface **266** of the body **260**.

In other exemplary embodiments of the image contrast grids **224** according to this invention, the x-ray absorbing material can be formed only on the side walls **268** defining the openings **262**. For example, in such exemplary embodiments, the x-ray absorbing material can form a hollow-cylindrical configuration in the openings **262**. In such exemplary embodiments, the x-ray absorbing material **264** can cover only portions of, or substantially the entire, side walls **268**.

In various exemplary embodiments of the image contrast grids according to this invention, the openings **262** formed in the body **260** have a quasi-periodic arrangement. However, in other exemplary embodiments of the image contrast grid **224**, the openings **262** can be formed in different patterns. For example, in the exemplary embodiment of the image contrast grid **324** shown in FIG. **8**, the openings **362** of the body **360** have a regular pattern. Other regular patterns of openings in the image contrast grids can also be formed.

Furthermore, in other exemplary embodiments of the image contrast grids according to this invention, the openings can be randomly formed. FIG. **9** illustrates an exemplary embodiment of an image contrast grid **424** having randomly formed openings **462** in the body **460**.

In the image contrast grid **224** shown in FIG. **7**, the x-ray absorbing material **264** completely fills the openings **262** along their entire lengths. Thus, the x-ray absorbing material **264** forms solid columns of x-ray absorbing material in the matrix of the body **260**. The columns of the x-ray absorbing material **264** have a generally cylindrical shape.

The body **260** can have any suitable configuration. A typical configuration for imaging applications is the illustrated generally rectangular shape. The body **260** includes the top surface **266**, a bottom surface **270** and side surfaces **272**. However, other configurations of the body **260**, such as square configurations, can also be formed. The dimensions of the body **260** can be varied to provide the desired cross-sectional area A of the top surface **266** and height h.

The body **260** can comprise any suitable material that is substantially transparent to x-rays. These materials can be inorganic and/or organic. Exemplary inorganic materials suitable for forming the body **260** include aluminum, aluminum alloys such as aluminum-nickel alloys, and metal oxides such as aluminum oxide.

The body **260** can also be formed of any suitable organic material. Exemplary plastics that can be used to form the body **260** include, for example, acrylics, such as polymethylmethacrylate (PMMA), and epoxies, such as SU-**8** epoxy, which is commercially available from Shell Chemical Company. The size of the openings formed in these materials may be different than those openings formed in metallic materials such as aluminum.

Other materials that can be used to form the body **260** include semiconductor materials, such as silicon. Silicon provides the advantage that it can be etched to form the openings **262** using well-known dry and wet etching techniques and other processes.

The x-ray absorbing material **264** that is formed in the openings **262** of the body **260** can be any suitable material that absorbs x-rays substantially without scattering the x-rays. The x-ray absorbing material **264** is applied in the openings **262** to absorb Compton-scattered x-rays that are scattered by the object to be imaged. Exemplary x-ray absorbing materials include lead, gold, platinum, tin, silver and mercury. Many exemplary embodiments of the image contrast grids **224** use lead as the x-ray absorbing material **264** because lead has excellent x-ray absorbing properties. In addition, lead is inexpensive and can be easily applied in the openings due to its low melting point.

The amount that the openings **262** in the body **260** of the image contrast grid **224** are filled by the x-ray absorbing material **264** can be characterized, for example, by two different factors. First, the fill amount can be characterized by the fill factor F. The fill factor F is defined as the ratio of the cross-sectional area of the x-ray absorbing material $A_{x\text{-}ray\ absorbing\ material}$ to the total cross-sectional area of the image contrast grid A_{grid}, in a plane parallel to the plane of the top surface **266** of the image contrast grid **224**, as follows:

$$F=A_{x\text{-}ray\ absorbing\ material}/A_{grid}$$

In general, at a given fill factor F, the detail of the image formed using the image contrast grid can be improved by increasing the pitch of the openings, which is the spacing between the openings.

Second, the fill amount of the openings **262** in the body **260** can be characterized by the open aperture ratio O, which reflects the cross-sectional area of the openings **262** that is not filled with the x-ray absorbing material **264**. The open aperture ratio is defined as the ratio of the total cross-sectional area of the open, non-filled portions of the openings A_{open} to the total cross-sectional area of the image contrast grid A_{grid}, in a plane parallel to the plane of the top surface **266** of the image contrast grid **224**, as follows:

$$O=A_{open}/A_{grid}$$

The open aperture ratio O and the fill factor F are related as:

$$O+F=1$$

The fill factor F, or the open aperture ratio O, affect the imaging performance of the image contrast grid **224** by affecting the amount of absorption of the x-rays by the x-ray absorbing material **264** formed in the openings. That is, because the x-ray absorbing material affects the percentage of the x-rays that pass through an object and impinge on the top surface **268** of the image contrast grid **224** in a direction normal to the top surface **268**, the fill amount of the openings **262** by the x-ray absorbing material **264** affects the percentage of these normal x-rays that can be absorbed by the image contrast grid **224**. Accordingly, increasing the fill factor F, or decreasing the open aperture ratio O, of the image contrast grid **224** thus increases the amount of the x-ray absorbing material **264** that can absorb the normal x-rays. Likewise, decreasing the fill factor F, or increasing the open aperture ratio O, of the image contrast grid **224** decreases the amount of the x-ray absorbing material **264** that can absorb the normal x-rays.

In accordance with this invention, the image contrast grids **224** can provide lower fill factors F, and thus higher open aperture ratios O, than those provided by known image contrast grids, such as the image contrast grid **124** shown in FIG. **6**. Open aperture ratios O approaching one are preferred. Accordingly, the image contrast grids **224** according to this invention absorb a lower percentage of the normal x-rays that impinge on them after having passed through an object to be imaged.

The columns of the x-ray absorbing material **264** shown in FIG. **7** have a diameter d and an inter-column spacing (pitch) P. A typical value for the diameter d is from about 0.1 μm to about 100 μm for body materials such as aluminum. A typical value of the pitch P is from about 0.2 μm to about 200 μm. A typical height h for the body is from about 10 μm to about 2000 μm. In various exemplary embodiments, the column diameter d satisfies the relationship:

$0.1\ \mu m < d \leq 0.5P$.

For non-metallic materials such as PMMA, the opening diameter d can typically be from about 10 μm to about 1000 μm.

The image contrast grid **224** can be formed using various exemplary embodiments of the methods according to this invention. A first exemplary embodiment of a method according to this invention comprises patterning the material of the body using conventional photolithographic techniques. For example, the openings can be formed in the masked body by wet or dry etching techniques, as described in U.S. Pat. No. 6,177,236, incorporated herein by reference in its entirety. The etching processes can form a pattern of openings **262** in the body **260** having a staggered arrangement.

The openings **262** can have the cylindrical shape shown in FIG. **7**. The openings **262** can alternatively have other cross-sectional shapes, such as square, rectangular, triangular, hexagonal or the like.

In various exemplary embodiments of the image contrast grid **224**, the height of the x-ray absorbing material **264** in the openings **262** is thicker than the absorption length of the x-rays. For typical x-ray applications, a height of 0.5–1 mm of lead is sufficient. For other materials, the desired height is related to the atomic number Z of the element. In various exemplary embodiments, the desired height is inversely proportional to Z^3.

After the openings **262** are formed in the body material **260** by dry or wet etching or some other suitable technique, the x-ray absorbing material **264** is applied in the openings **262**. An exemplary technique for applying the x-ray absorbing material **264** in the openings **262** is to dip the body **260** into a bath of a molten metal. For example, the body material, such as aluminum, can be wetted with the x-ray absorbing material, such as lead, by dipping the aluminum into a molten lead bath. During the dipping process, the lead flows into the openings **262**. The melted x-ray absorbing material **264** can partially or substantially completely fill the openings. Various factors that influence the fill amount of the melted x-ray absorbing material **264** into the openings **262** include the size of the openings **262**, the length of the openings **262**, and the amount of time the body **260** is dipped into the melted x-ray absorbing material **264**.

To enhance the flow of the x-ray absorbing material **264** into the openings **262**, a flux may be utilized in various exemplary embodiments of the dipping process. Fluxes can be especially advantageous for openings that have a small diameter and/or a relatively long length, and where a high fill amount of the x-ray absorbing material **264** is desired in the openings **262**.

The flow of the x-ray absorbing material **264** into the openings **262** can also be enhanced by applying pressure to the melted x-ray absorbing material **264** so that the melted x-ray absorbing material **264** is injected into the openings under pressure.

Alternatively, in other exemplary embodiments, a pressure gradient can be formed across the thickness of the body **260**, to enhance the filling of the openings **262** by the x-ray absorbing material **264**. For example, a low pressure can be created at a surface of the body **260**, such as, for example, by a vacuum pump. An elevated pressure can be applied at an opposite surface of the body, to increase the pressure gradient across the body **260**. Typically, the pressure gradient is created in the thickness direction of the body **260**.

As stated above, in various exemplary embodiments, the side walls **268** of the openings **262** in the body **260** can be coated with the x-ray absorbing material **264** along only a portion of the length of the side walls **268**, instead of partially or substantially completely filling the openings **262** with the x-ray absorbing material. Coating only the side walls **268** of the openings **262** with the x-ray absorbing material **264** can significantly improve the imaging performance of the image contrast grid **224**, by increasing the open aperture ratio O.

Any suitable physical, chemical or electrochemical coating process can be used to coat the side walls **268** of the openings **262** of the body **260** with the x-ray absorbing material **264**. Exemplary coating processes include physical vapor vacuum deposition, electrochemical deposition, chemical vapor deposition, chemical liquid deposition and the like. The coating process forms a coating on the side walls **268** that has a suitable thickness and length to provide the desired level of coverage for x-ray absorption by the image contrast grid **224**.

The coating thickness of the x-ray absorbing material **264** formed on the side walls **268** of the openings **262** is preferably no greater than about the radius of the openings **262**. The coatings of the x-ray absorbing material **264** on the side walls **268** of the openings **262** improves the imaging performance of the image contrast grids by providing a higher open aperture ratio O. That is, the resulting hollow coatings, having, e.g., a hollow cylinder configuration, provide a higher open aperture ratio O than is achieved by reducing the diameter d and filling the openings **262** to a greater level, to provide the same desired open aperture ratio O.

Other exemplary embodiments of the methods of forming the image contrast grids comprise coating the openings **262** in the body **260** with the x-ray absorbing material **264** by using any suitable electroplating technique. These embodiments are particularly useful for forming image contrast grids **224** having a random pattern of the openings **262**.

In still other exemplary embodiments of the methods of forming image contrast grids according to this invention, an etching process, such as an anodic etching process, can be used in combination with photolithography to form the openings **262** in the body **224**. For example, as described in U.S. Pat. No. 6,177,236, the body is anodically etched using a suitable etching solution to form micropores. The micropores are separated from each other by thin walls. For aluminum, the walls between the micropores comprise aluminum oxide. The micropores typically have a diameter of 0.3 μm or less.

The micropores may then be filled with the x-ray absorbing material **264** to form an image contrast grid. In other embodiments, the micropores formed by anodic etching are aggregated, and the thin walls separating the micropores are removed. Oxide etching using any suitable oxide etch solution for the material forming the body can be employed to selectively remove the thin walls after a suitable application of photoresist or other patterned masking material.

The mask and photoresist can be removed during the oxide etching step by suitable selection of the oxide etch, or can alternatively be removed in a separate step, or left.

By combining anodic etching and oxide etching processes, the resulting openings formed in the body are suitably sized to allow the x-ray absorbing material to be applied into the openings. The exemplary methods according to this embodiment can be used to form random opening patterns.

Other exemplary embodiments of the methods of forming the image contrast grids **224** comprise the use of a photoimagable material. The photoimagable material can be, for example, PMMA or SU-**8**. The photoimagable material is patterned with holes **262** and is coated or filled with the x-ray absorbing material **264** using any suitable coating process such as sputtering, or by chemical or electrochemical processes.

Alternatively, a seed layer of a conductive material can be deposited on the photoimagable material and any suitable x-ray absorbing material **264** can then be applied over the seed layer by any suitable process. For example, lead can be applied over the seed layer by an electroplating process.

The image contrast grids **224** with an opening diameter of less than about 10 μm also have improved scatter rejection, while leaving at most a minimal trace of the image contrast pattern on the final image. Accordingly, because the openings have a small size, the Bucky system does not need to be used during imaging for the image contrast grids **224** formed according to these embodiments.

An important aspect of imaging is achieving a suitable focus of the image. For some imaging applications, a parallel column structure as illustrated in FIG. **7** is not completely satisfactory. That is, because the x-rays that arrive at the imager are focused on the x-ray source, a focused image contrast grid having a focal length that equals the distance between the grid and the source is used.

Micromachined openings, such as the openings formed in the body material by etching processes, typically grow in a direction substantially normal to the top surface of the body. Accordingly, this opening orientation produces parallel devices having an infinite focal length.

According to this invention, it is desirable that the x-rays that pass through the object strike the top surface of the image contrast grid **224** at an angle normal to the top surface. The x-rays that strike the top surface at a normal angle have a high level of transmission through the image contrast grid **224**. In contrast, the x-rays that strike the top surface at an acute angle of less than 90° are highly attenuated, i.e., absorbed.

The rejection ratio R is related to the amount of x-rays that are absorbed versus the amount of x-rays that are transmitted at a given angle of incidence of the x-rays. The rejection ratio R is given by:

$$R(\theta)=A(\theta)/T(\theta)$$

where:

$A(\theta)$ is the absorption of the x-rays at an angle of incidence of θ of the x-rays; and

$T(\theta)$ is the transmission of the x-rays at an angle of incidence of θ of the x-rays.

Accordingly, the rejection ratio R decreases toward zero as the amount of x-rays that are absorbed decreases and the amount transmitted increases. The rejection ratio R increases toward infinity as the amount of x-rays that are absorbed increases and the amount transmitted decreases. The image contrast grids **224** according to this invention can provide increased rejection ratios R, corresponding to a high level of x-ray transmission and a low level of x-ray absorbance.

As stated above, the rejection ratio R is dependent on the angle of incidence of the x-rays on the top surface of the image contrast grid **224**. FIG. **10** illustrates the relationship between the angle of incidence of x-rays on the top surface of the image contrast grid versus the rejection ratio R of the x-rays for an image contrast grid **224** according to this invention (curve A), and for a conventional image contrast grid having a sandwich structure such as the image contrast grid **124** shown in FIG. **6** (curve B). As shown, the rejection ratio R increases as the angle of incidence of the x-rays increases, reflecting a higher percentage of the x-rays being absorbed as opposed to being transmitted.

Because the image contrast grids can provide improved levels of x-ray transmission, the dose that is delivered to patients during medical imaging procedures is significantly reduced because fewer orthogonal x-rays are absorbed by the image contrast grids.

As shown in FIGS. **11** and **12**, to provide the desired level of focus during imaging procedures, various exemplary embodiments of the image contrast grids **524** according to this invention have a contoured top surface **566** at which the x-rays impinge on the image contrast grid. As shown in FIGS. **11** and **12**, the top surface **566** includes surface regions **5662**, **5664**, **5666** and **5668**, each oriented at a different angle relative to the direction N; i.e., the surface regions are skewed relative to the normal N. The surface region **5662** is perpendicular to the normal N, while the surface regions **5664**, **5666** and **5668** are oriented at different acute angles relative to the direction N. Consequently, the x-rays **5322**, **5324**, **5326** and **5328** strike each respective surface region **5662**, **5664**, **5666** and **5668**, at an angle of about 90°. By orienting the surface regions **5662**, **5664**, **5666** and **5668** in this manner, the level of x-ray transmission increases, and the corresponding rejection ratio R for each of these surface regions approaches zero. Accordingly, the overall rejection ratio R of the image contrast grid **524** also increases.

According to this invention, the top surface **566** of the image contrast grid **524** can be contoured by any suitable process. For example, the top surface **566** of the body can be stamped. Alternatively, the upper surface **566** of the body can be contoured by any suitable milling procedure. For example, a milled pattern can be formed in the upper surface **566** using a milling machine, such as a computer-controlled milling machine that can provide precise patterns. Aluminum materials are relatively soft and can be easily machined and contoured.

As shown in FIG. **12**, the pattern formed in the contoured top surface **566** of the body can include concentric rings. Each ring can form one of the surface regions **5662**, **5664**, **5666** and **5668** that is orthogonal to the focal point. The distance between the rings can be varied to provide the desired pattern.

When the body material is etched or anodized, the pores grow substantially orthogonal to the local surface orientation. Accordingly, the openings **5622**, **5624**, **5626** and **5628** associated with the respective surface regions **5662**, **5664**, **5666** and **5668** are generally parallel to each other. However, the openings **5622**, **5624**, **5626** and **5628** have different orientations from each other. Thus, the x-ray absorbing material **5622**, **5624**, **5626** and **5628** formed in the respective openings **5622**, **5624**, **5626** and **5628** does not form an entirely parallel structure of columns or x-ray absorbing material configurations.

The rings are formed in the top surface of the body with a desired pitch p, which is the distance between the rings. The pitch of the rings can be varied to affect the sensitivity of the grid geometry to misalignment. For a one-degree variation across the grid, the pitch is preferably smaller than the focal length f divided by 30 (i.e., p=f/30). This pitch p can be easily achieved in various exemplary embodiments of the methods of this invention, even for short focal lengths f that correspond to a small desired pitch p. Image quality considerations can, in some applications of the image contrast grids, require a finer pitch.

The various exemplary embodiments of the micromachined image contrast grids **224**–**524** of this invention provide advantages over known grid structures. First, the image contrast grids **224–524** according to this invention can achieve a two-dimensional antiscatter geometry.

Second, the openings, and the x-ray material formed in the openings, provide an increased open aperture ratio O. For example, the open aperture ratio of the image contrast grids can be at least about 90%. In contrast, known image contrast grids have an open aperture ratio of only about 80%.

Third, as explained above, the Bucky system typically does not need to be used during use of the image contrast grids according to this invention because the openings can be formed with sufficiently small sizes to not be visible in most imaging modes. For example, the image contrast grids can be formed with up to about 1000 openings per mm. In contrast, known image contrast grids **224–524** have less than 10 openings per mm.

However, in some applications, the particular focusing system that is used can cause image artifacts. If desired, these artifacts can be removed by using the Bucky system.

In other exemplary embodiments, the above-described methods can be used to form the body of the image contrast grid from an x-ray absorbing material rather than from an x-ray transparent material. The openings in the body are then filled with an x-ray transparent material to form a complementary structure to those of the above-described embodiments. The openings in the body can be partially filled by the x-ray transparent material. The x-ray transparent material can be formed substantially only on the walls of the openings. If the openings are left unfilled, then the body formed of the x-ray absorbing material would require an x-ray transparent support structure such as an aluminum plate. If the openings are filled with aluminum or plastic or any other suitable x-ray transparent materials having desirable structural properties, then the body will be self-supporting. Such structures are capable of high open aperture ratios, typically above 90%.

In further exemplary embodiments, the above-described embodiments can be modified by the use of casting processes to reduce the cost of making the image contrast grids, or to transfer a pattern from one material to another material.

It is contemplated that the image contrast grids **224–524** can be used in different applications. For example, another exemplary application for collimating structures for x-rays is in single photon emission computer tomography (SPECT) cameras. In these devices, the collimator allows a two-dimensional x-ray detector to function as a camera, by detecting photons based on their direction rather than just on the locations at which they strike the imager. The imaging, therefore, does not depend on a pointlike x-ray source for forming images.

In this application in SPECT cameras, a radioisotope is administered to a patient before undergoing imaging. The radioisotope has a characteristic x-ray or gamma ray emission spectrum. The radioisotope concentrates within a particular organ or structure within the patient's body, and a computed tomography approach is used to reconstruct a three-dimensional image of the concentrated region. However, SPECT camera performance is dependent on, and is often limited by, the performance of the collimator.

For SPECT cameras, the x-ray absorbing material formed in the openings will typically have a height of 5 mm to 5 cm for some medical imaging procedures, depending on the particular radioisotope that is used.

While the invention has been described in conjunction with the specific embodiments described above, it is evident that many alternatives, modifications and variations are apparent to those skilled in the art. Accordingly, the preferred embodiments of the invention as set forth above are intended to be illustrative and not limiting. Various changes can be made without departing from the spirit and scope of the invention.

What is claimed is:

1. An image contrast grid for the x-ray imaging of objects, comprising:

a body comprising a second material that absorbs x-rays without substantially scattering the x-rays, the body forming a continuous matrix and including:

a first surface where the x-rays enter the image contrast grid;

a second surface opposite to the first surface where the x-rays exit the image contrast grid; and

openings that extend at least partially from the first surface to the second surface; and

a first material that is at least substantially transparent to x-rays disposed in the openings,

wherein the body includes a plurality of groups of the openings, the first surface of the body comprises a plurality of surface regions including a central surface region that is oriented perpendicular to a normal direction and other surface regions that are (i) disposed radially outward from the central region and (ii) each oriented at a different acute angle relative to the normal direction, the openings in each of the respective groups of openings are (i) parallel to each other and (ii) oriented perpendicular to one of the surface regions.

2. The image contrast grid of claim **1**, wherein the image contrast grid removes Compton scattered x-rays in two coplanar dimensions.

3. The image contrast grid of claim **1**, wherein the first material is inorganic.

4. The image contrast grid of claim **1**, wherein the first material is organic.

5. The image contrast grid of claim **1**, wherein the first material comprises aluminum or aluminum oxide and the second material comprises lead.

6. The image contrast grid of claim **1**, wherein at least some of the openings in the body extend from the first surface to the second surface.

7. The image contrast grid of claim **1**, wherein the openings in the body are elongated.

8. The image contrast grid of claim **1**, wherein the first material is air.

9. An x-ray imaging system for imaging objects, comprising:

an x-ray source that emits x-rays;

an image contrast grid according to claim **1** positioned such that x-rays emitted by the x-ray source that pass through the object impinge on the first surface; and

an image plane facing the second surface of the image contrast grid.

10. The x-ray imaging system of claim **9**, wherein the image contrast grid is stationary during imaging, and the image contrast grid removes Compton scattered x-rays that pass through the object in two coplanar dimensions of the image contrast grid.

11. The image contrast grid of claim **1**, wherein the openings in the body are randomly arranged.

12. The image contrast grid of claim **1**, wherein the openings in the body are arranged in a pattern.

13. The image contrast grid of claim **1**, wherein the image contrast grid has an open aperture ratio of at least about 90%.

14. The image contrast grid of claim **1**, wherein the openings are substantially filled by the first material.

15. The image contrast grid of claim 1, wherein the openings are only partially filled by the first material.

16. The image contrast grid of claim 1, wherein the openings are defined by walls, and the first material is formed substantially only on the walls.

17. The image contrast grid of claim 1, wherein the openings have a diameter of about 0.3 μm and a length of about 300 μm.

18. A method of imaging an object, comprising:

emitting x-rays from an x-ray source that impinge on the object;

removing Compton scattered x-rays that pass through the object with an image contrast grid according to claim 1; and

forming an image of the object on an image plane from the x-rays that pass through the image contrast grid.

19. The method of claim 18, wherein the image contrast grid is stationary during imaging of the object, and the image contrast grid removes the Compton scattered x-rays that pass through the object in two coplanar dimensions of the image contrast grid.

20. A method of making an image contrast grid, comprising:

forming a body comprising one of a first material that is at least substantially transparent to x-rays and a second material that absorbs x-rays without substantially scattering the x-rays, the body forming a continuous matrix and including:

a first surface where the x-rays will enter the image contrast grid;

a second surface opposite to the first surface where the x-rays will exit the image contrast grid; and

electrochemically etching the body to form micropores separated by walls in the body;

aggregating the micropores by oxide etching to form openings in the body that extend at least partially from the first surface to the second surface; and

forming another of the first material and the second material in the openings,

wherein (i) when the body comprises the first material, the second material is formed in the openings, and (ii) when the body comprises the second material, the first material is formed in the openings.

21. The method of claim 20, wherein the openings have a diameter of about 0.3 μm and a length of about 300 μm.

22. The method of claim 20, wherein the another of the first material and the second material is formed substantially only on the walls of the openings.

23. A method of making an image contrast grid, comprising:

forming a body comprising a second material that absorbs x-rays without substantially scattering the x-rays, the body forming a continuous matrix and including:

a first surface where the x-rays will enter the image contrast grid;

a second surface opposite to the first surface where the x-rays will exit the image contrast grid; and

forming openings in the body that extend at least partially from the first surface to the second surface; and

forming a first material that is at least substantially transparent to x-rays in the openings,

wherein the body includes a plurality of groups of the openings, the method further comprises machining the first surface of the body to form a plurality of surface regions including a central surface region that is oriented perpendicular to a normal direction and other surface regions that are (i) disposed radially outward from the central region and (ii) each oriented at a different acute angle relative to the normal direction, the openings in each of the respective groups of openings are (i) parallel to each other and (ii) oriented perpendicular to one of the surface regions.

24. The method of claim 23, wherein the first material comprises aluminum or aluminum oxide.

25. The method of claim 23, wherein the second material comprises lead.

26. The method of claim 23, wherein at least some of the openings formed extend from the first surface to the second surface.

27. The method of claim 23, wherein the openings in the body are elongated.

28. The method of claim 23, wherein the openings are formed in the body in a random arrangement.

29. The method of claim 23, wherein the openings are formed in the body in a regular pattern.

30. The method of claim 23, wherein the image contrast grid has an open aperture ratio of about 90%.

31. The method of claim 23, wherein the openings are substantially filled by the first material.

32. The method of claim 23, wherein the openings are only partially filled by the first material.

33. The method of claim 23, wherein the openings are defined by walls, and the first material is formed substantially only on the walls.

34. The method of claim 23, wherein the openings have a diameter of about 0.3 μm and a length of about 300 μm.

35. The method of claim 23, wherein the openings are formed by etching.

36. The method of claim 23, wherein the openings are formed by electrochemical etching.

37. An image contrast grid for the x-ray imaging of objects, comprising:

a body comprising one of a first material that is at least substantially transparent to x-rays and a second material that absorbs x-rays without substantially scattering the x-rays, the body forming a continuous matrix and including:

a first surface where the x-rays enter the image contrast grid;

a second surface opposite to the first surface where the x-rays exit the image contrast grid; and

a plurality of groups of openings that extend from the first surface toward the second surface; and

another of the first material and the second material disposed in the openings,

wherein the first surface of the body comprises a plurality of surface regions including a central surface region that is oriented perpendicular to a normal direction and other surface regions that are (i) disposed radially outward from the central region and (ii) each oriented at a different acute angle relative to the normal direction, the openings in each of the respective groups of openings are (i) parallel to each other and (ii) oriented perpendicular to one of the surface regions.

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